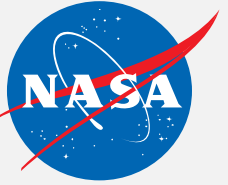


National Aeronautics and
Space Administration



ARSET

Applied Remote Sensing Training

<http://arset.gsfc.nasa.gov>

 @NASAARSET

Remote Sensing of Trace Gases

Melanie Follette-Cook and Pawan Gupta

Satellite Remote Sensing of Air Quality

Tuesday, Sep 19, 2017 – Thursday, Sep 21, 2017

University of California, Riverside

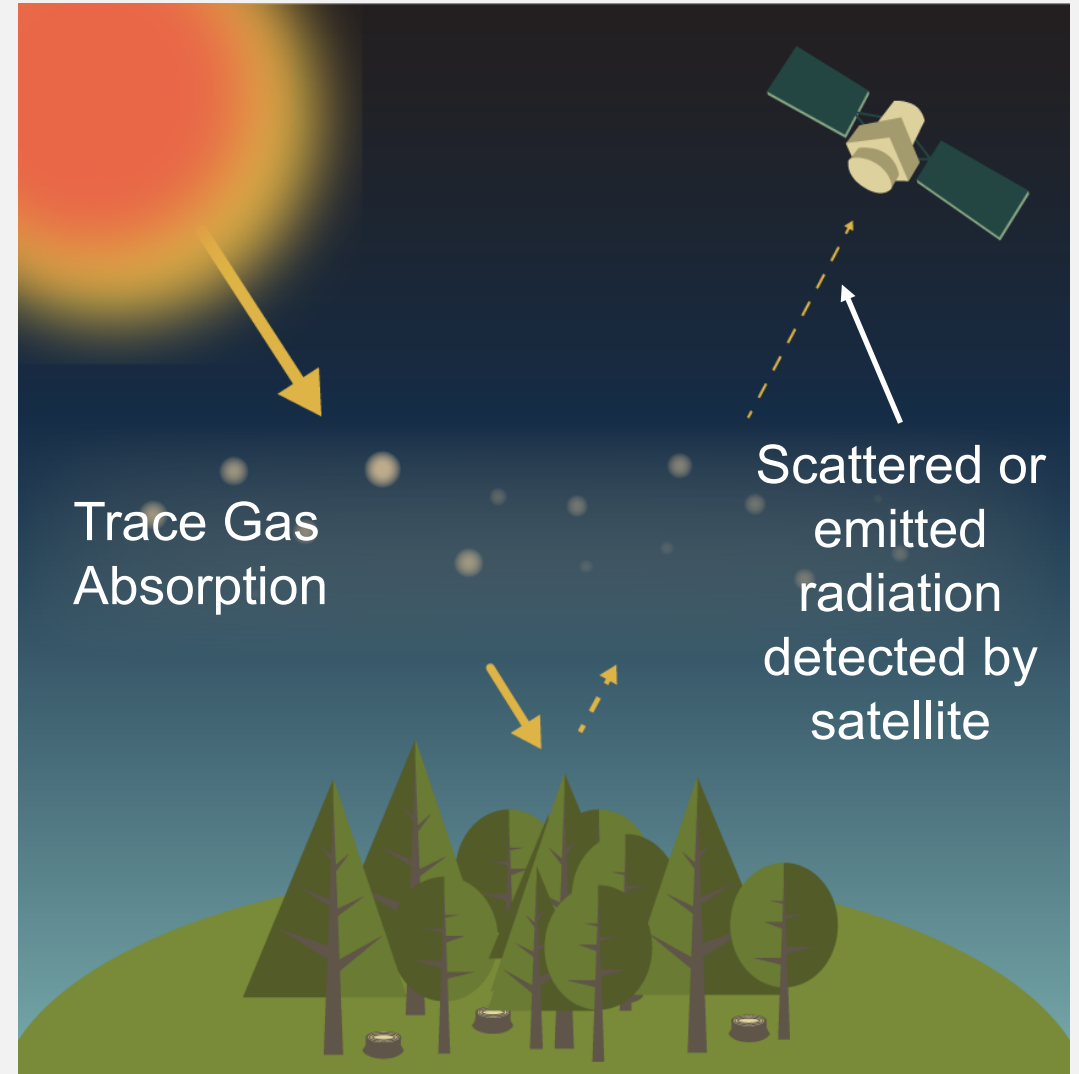
Satellite Remote Sensing of Trace Gases for Air Quality

Overview

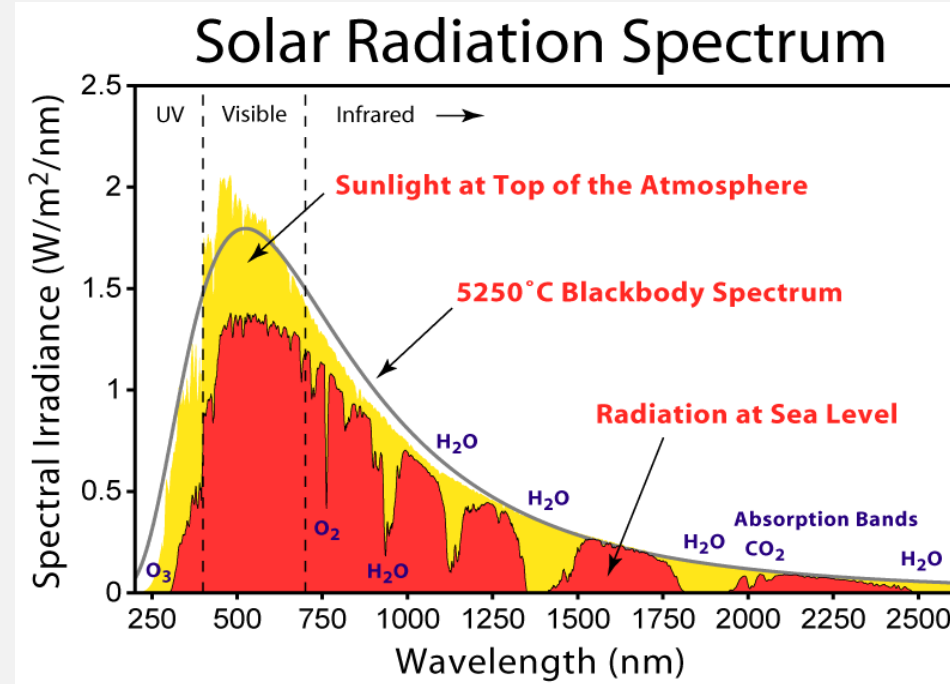
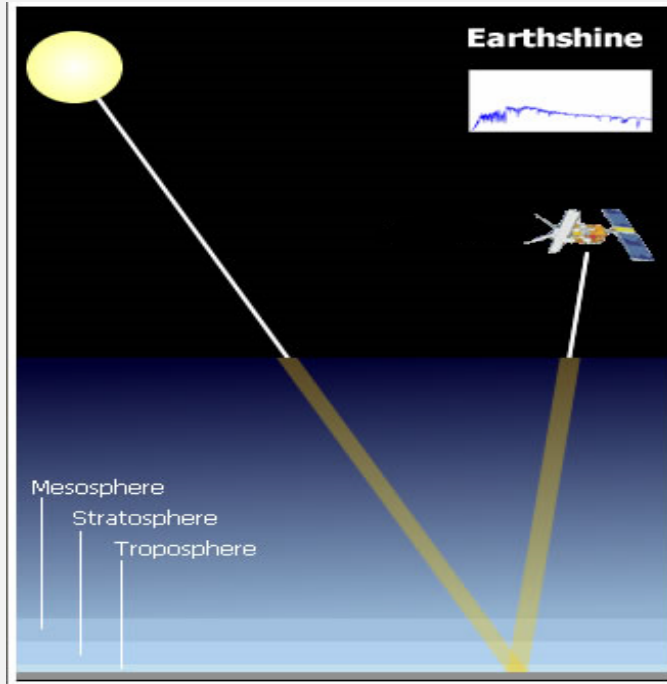
- **This presentation will cover several trace gases relevant to air quality**
 - O₃, HCHO, NO₂, SO₂, and CO

Measuring Trace Gases from Space

- Satellites detect backscattered UV/Vis and/or emitted thermal radiation
- We know the distinct absorption spectra of each trace gas
- We can identify a “spectral fingerprint” for each atmospheric constituent
- Retrieval algorithms (a model) infer physical quantities such as number density, partial pressure, and column amount



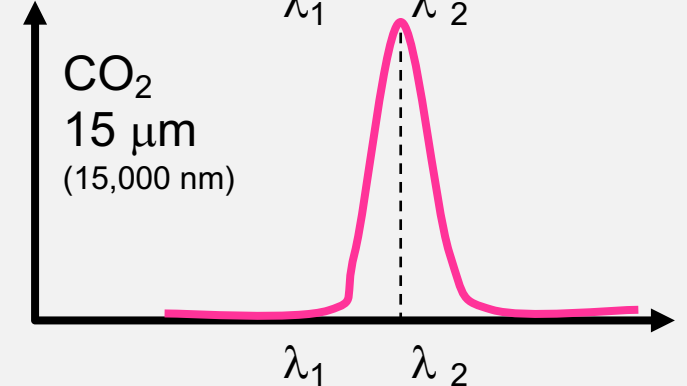
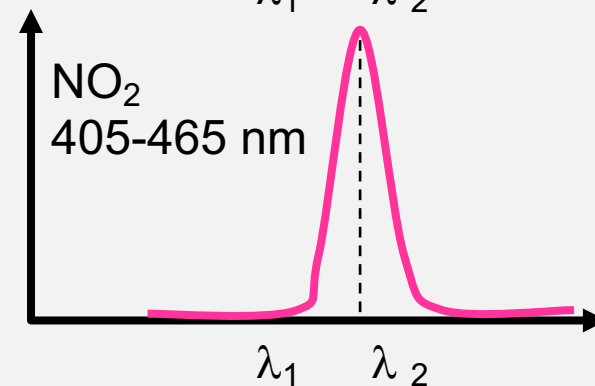
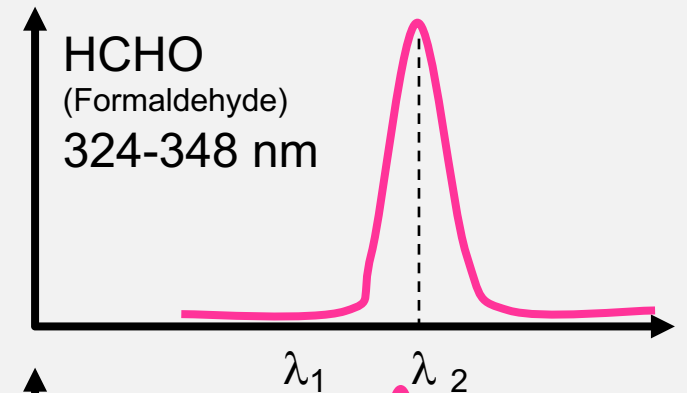
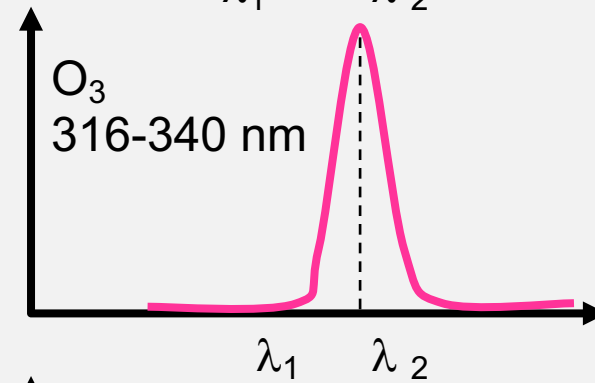
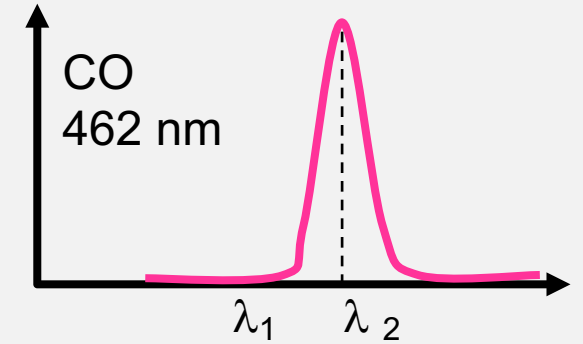
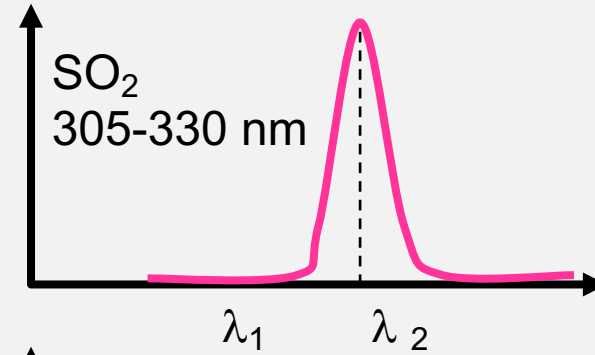
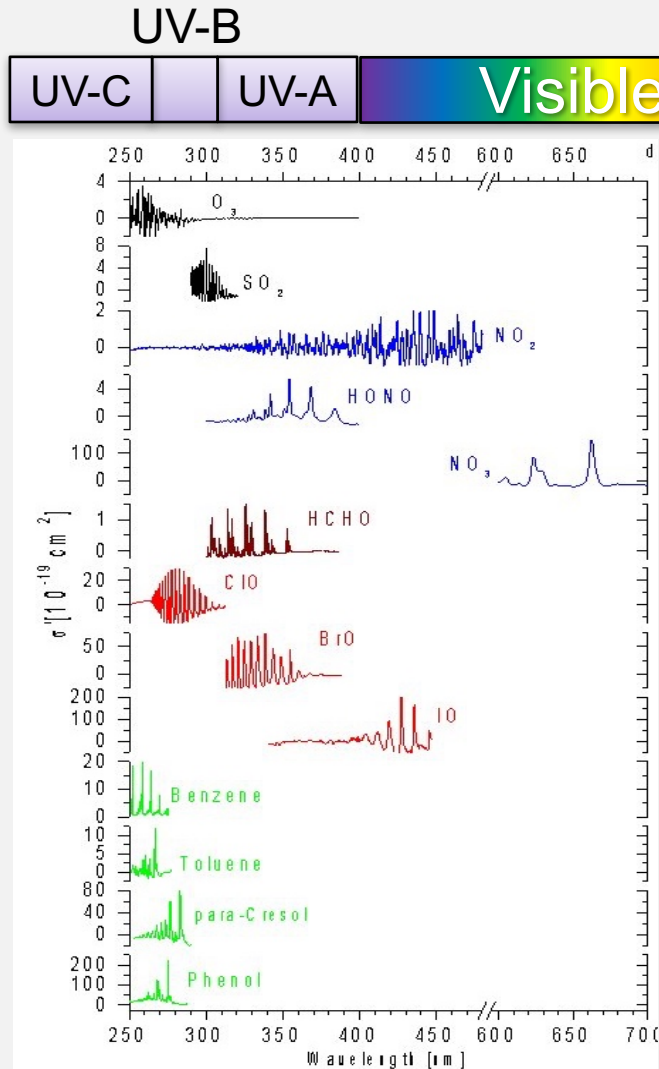
How Satellites Measure Trace Gases



- Trace gases use the signature of gas absorption
- All satellite remote sensing measurements of the troposphere are based on the use of electromagnetic radiation and its interaction with constituents in the atmosphere

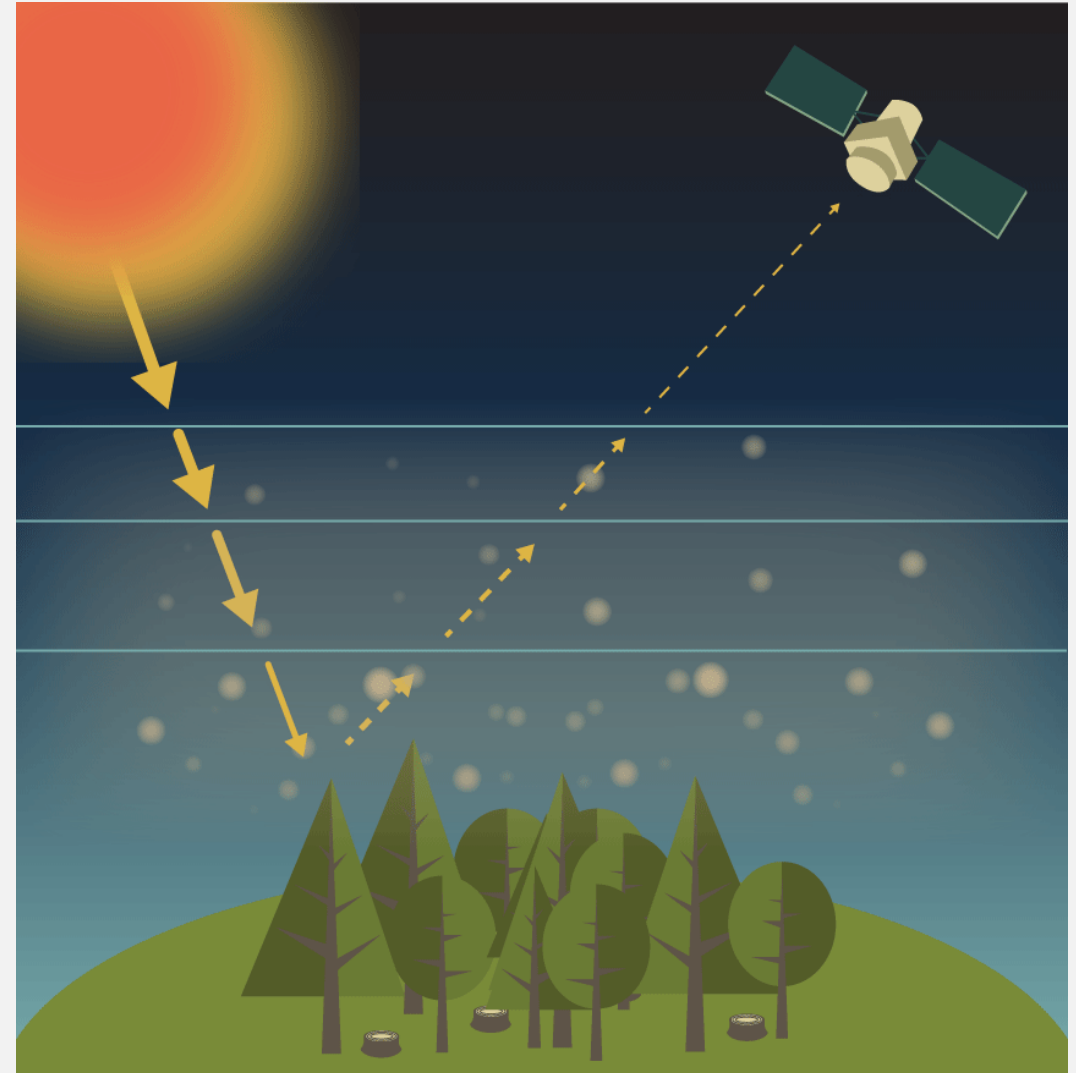
Image Credit (Right): [Wikipedia, Solar Spectrum](#)

Satellite Measurements Take Advantage of Distinct Absorption Spectra



Vertical Distribution

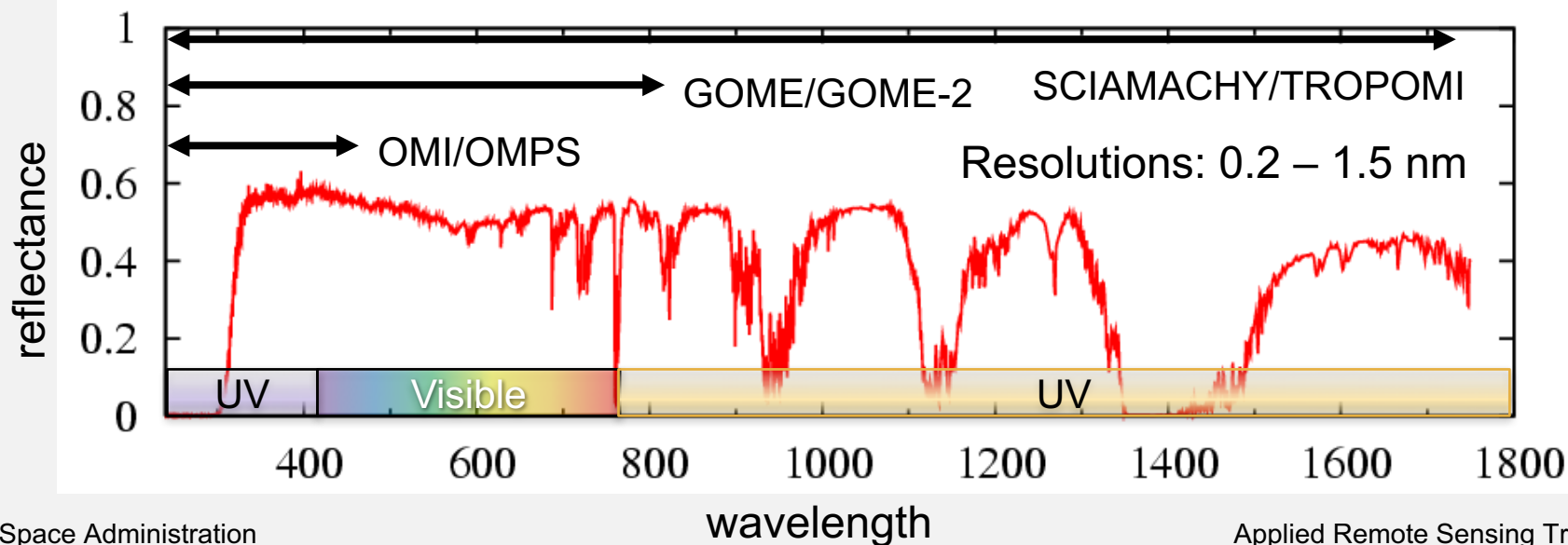
- Very little information can be obtained on the vertical distribution of trace gases in the troposphere from a nadir view
- Measurements techniques using different wavelengths (e.g. combining UV, visible, and IR measurements) can provide some vertical information
 - The penetration depth of photons increases with increasing wavelengths
 - Example: volcanic plumes of SO₂



Hyperspectral Instruments

Current and Future Satellite UV-Visible Spectrometers

Instrument	Satellite	Wavelength
GOME	ERS-2	240 – 800 nm
SCIAMACHY	Envisat	240 – 1750 nm
OMI	EOS-Aura	270 – 500 nm
GOME-2	Metop-A	240 – 800 nm
OMPS	Suomi-NPP	250 – 400 nm
TROPOMI	Sentinel-5P	270 – 775 nm, 2305 – 2385 nm



Data Formats & Resolutions

Data Level	Description
Level 0	Raw data at full instrument resolution
Level 1A	Raw data that have been time-referenced and supplemented with information such as radiometric and geometric calibration coefficients and geo-referencing parameters. These are computed and appended, but not applied to Level 0 data.
Level 1B	Level 1A data that has been processed to sensor units (not all instruments have Level 1B source data)
Level 2	Derived geophysical variables at the same resolution and location as Level 1 source data
Level 2G & 3	Variables mapped on uniform space-time grid scales, usually with some completeness and consistency
Level 4	Model output or results from analyses of lower level data (e.g. variables derived from multiple measurements)

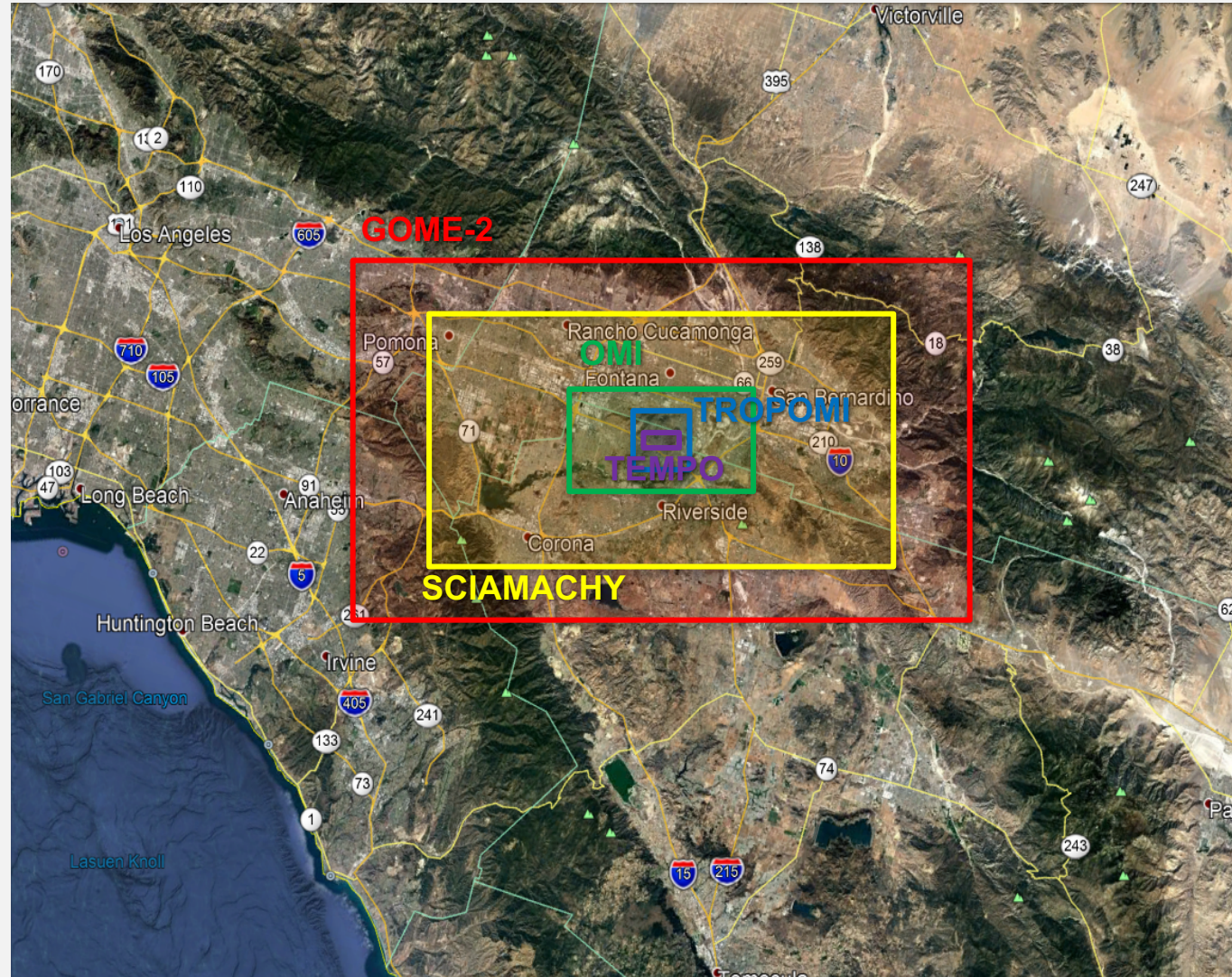
Using Level 3 vs. Level 2 Data

- Advantages
 - Uniform grid
 - One file per day
 - Smaller sized files
 - Quality flags and filtering criteria have been applied
- Limitations
 - Typically at coarser resolution than L2
 - L2 observation typically at the same location as the L1 source data

Spatial Resolution: Trace Gases

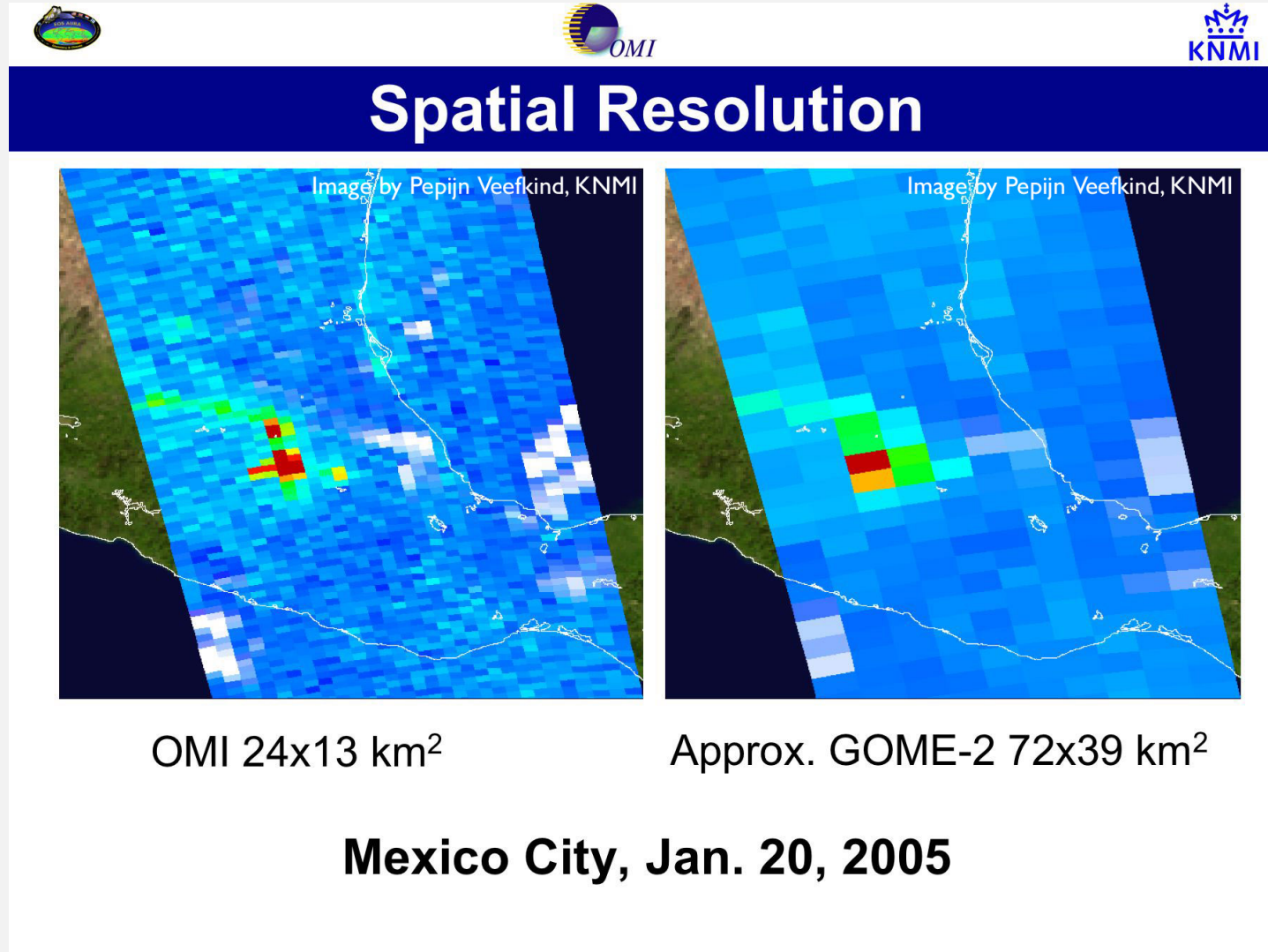
- Spatial resolution of current satellite instruments (10s of km diameter)
 - good enough to map tropospheric concentration fields on local to regional scales
 - fine enough to resolve individual power plants and large cities
- For species with short atmospheric lifetimes (e.g. NO₂), averaging over larger satellite pixels can lead to significant dilution of signals from point sources, complicating quantitative analysis and separation of emission sources
- For quantitative analysis: Level 2 and high resolution gridded Level 3 data are optimal

Evolution of Spatial Resolution

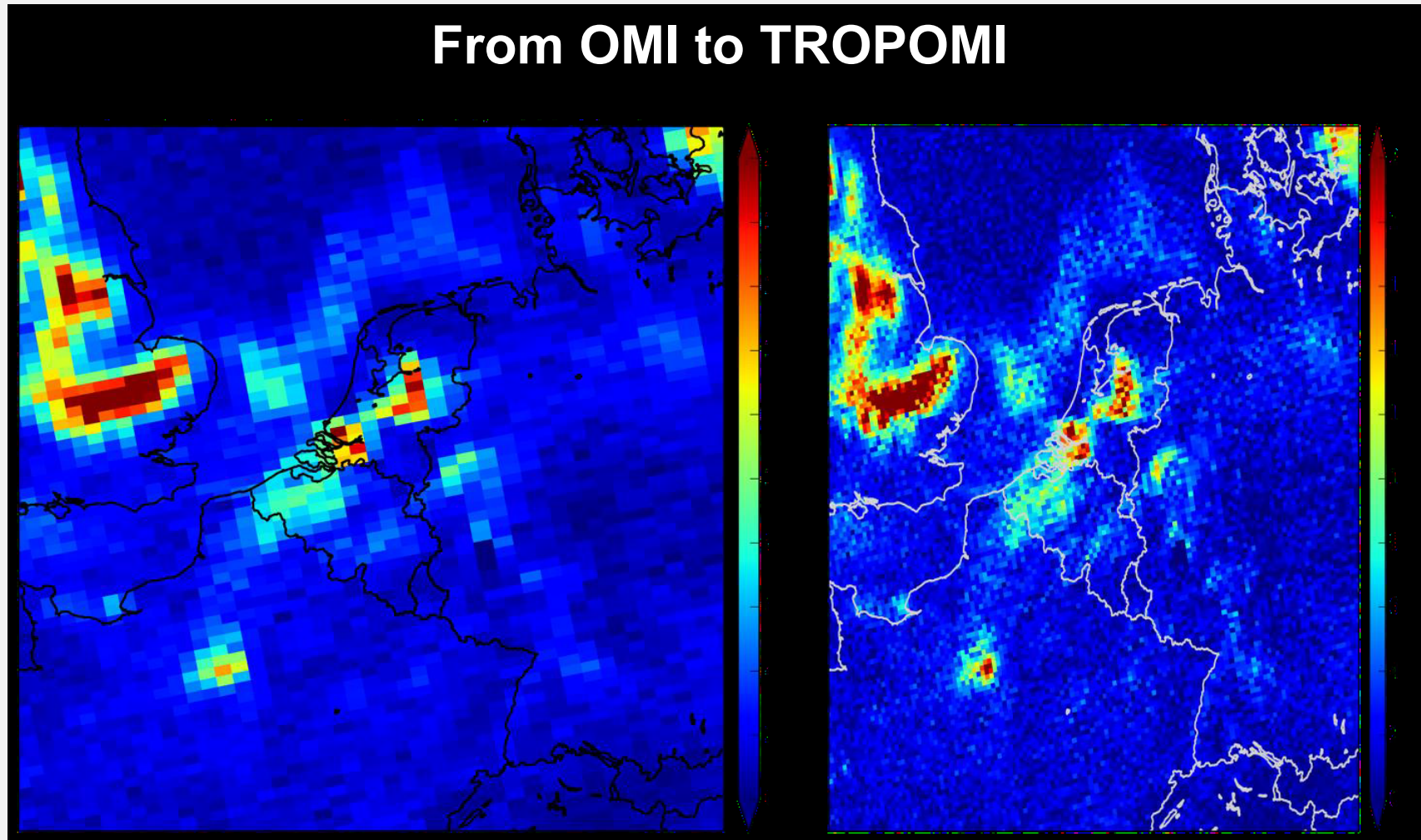


GOME-2
SCIAMACHY
OMI
TROPOMI
TEMPO

Perspective...



Perspective...



Data from the ESA ISOTROP Project, plots from P. Levelt (KNMI)

Quantification of Gas Abundances - Units

Satellite Tracer	Units
OMI O ₃ , SO ₂	Dobson Units (DU)
OMI NO ₂ , Column Amounts (also AIRS and MOPITT CO)	Molecules/cm ²
AIRS and MOPITT CO Vertical Levels	Volume Mixing Ratio (ppmv, ppbv, pptv)

1 DU = 2.69×10^{16} molec/cm²

ppm = 1 molec in 10^6 (or one part per million)

ppb = 1 molec in 10^9

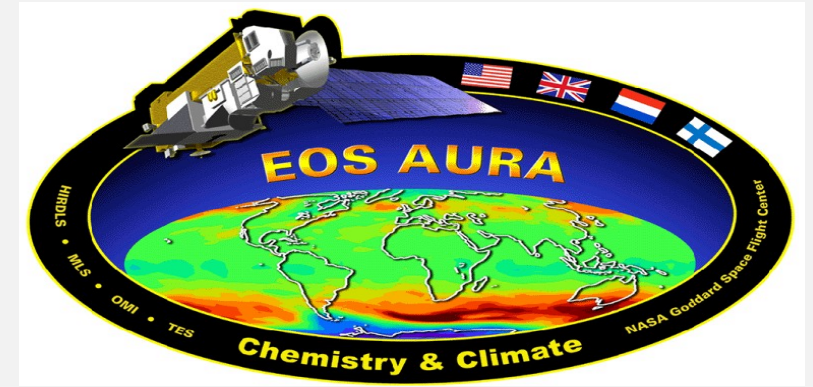
ppt = 1 molec in 10^{12}



OMI

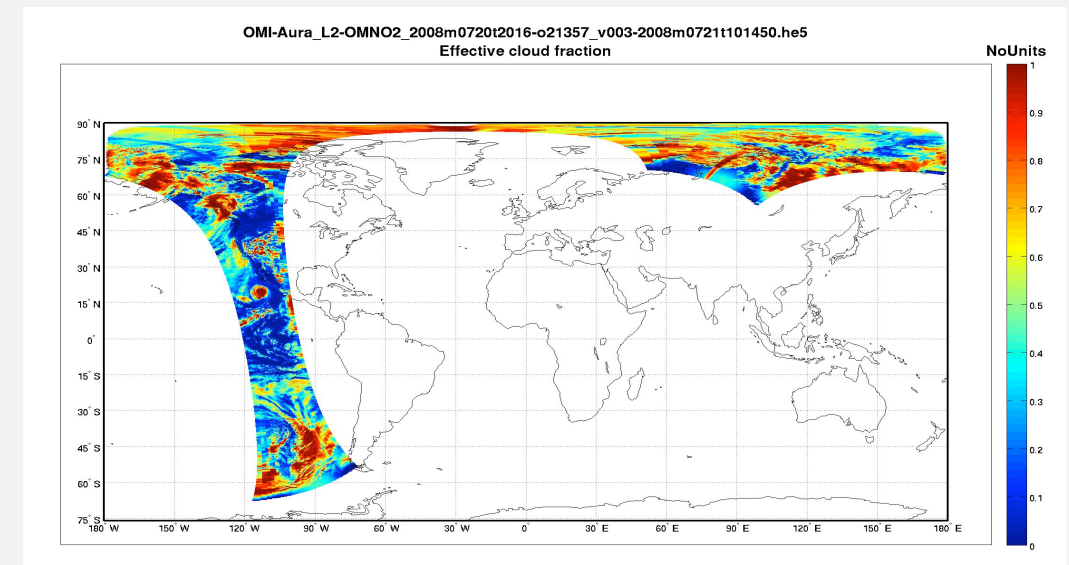
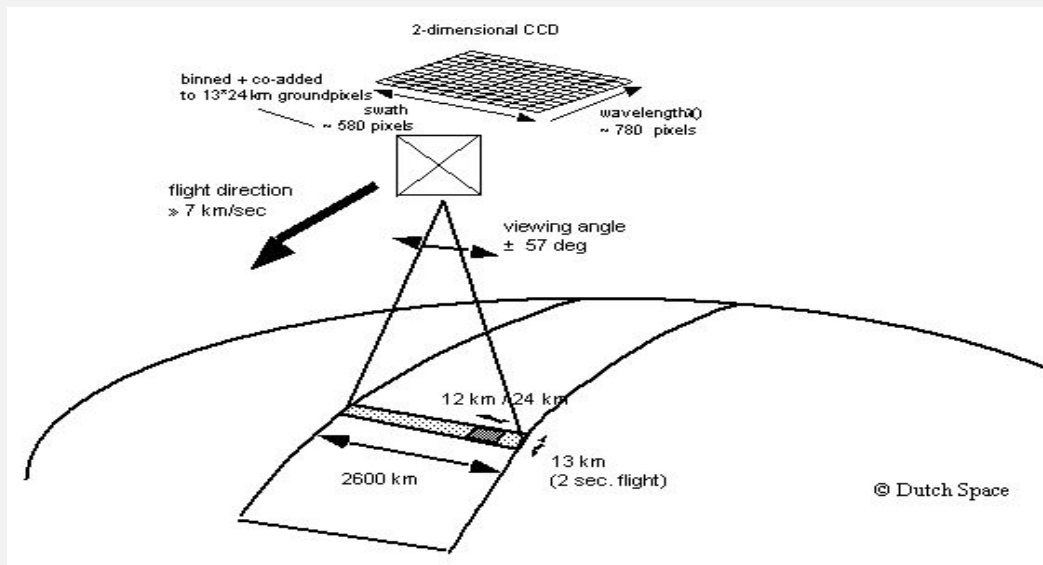
Ozone Measuring Instrument (OMI)

- Launched July 15, 2004
 - NASA EOS Aura Satellite
 - Nadir-viewing UV/Visible
 - 270 – 310 nm at 0.6 nm
 - 310 – 500 nm at 0.45 nm
 - 1:45 p.m. equatorial crossing time
 - 13x24 km² at nadir
 - Daily global coverage
- Products
 - Total Column O₃
 - Tropospheric Column O₃
 - Aerosol optical depth (in UV)
 - Column Formaldehyde
 - Column NO₂
 - Tropospheric column NO₂
 - Column SO₂



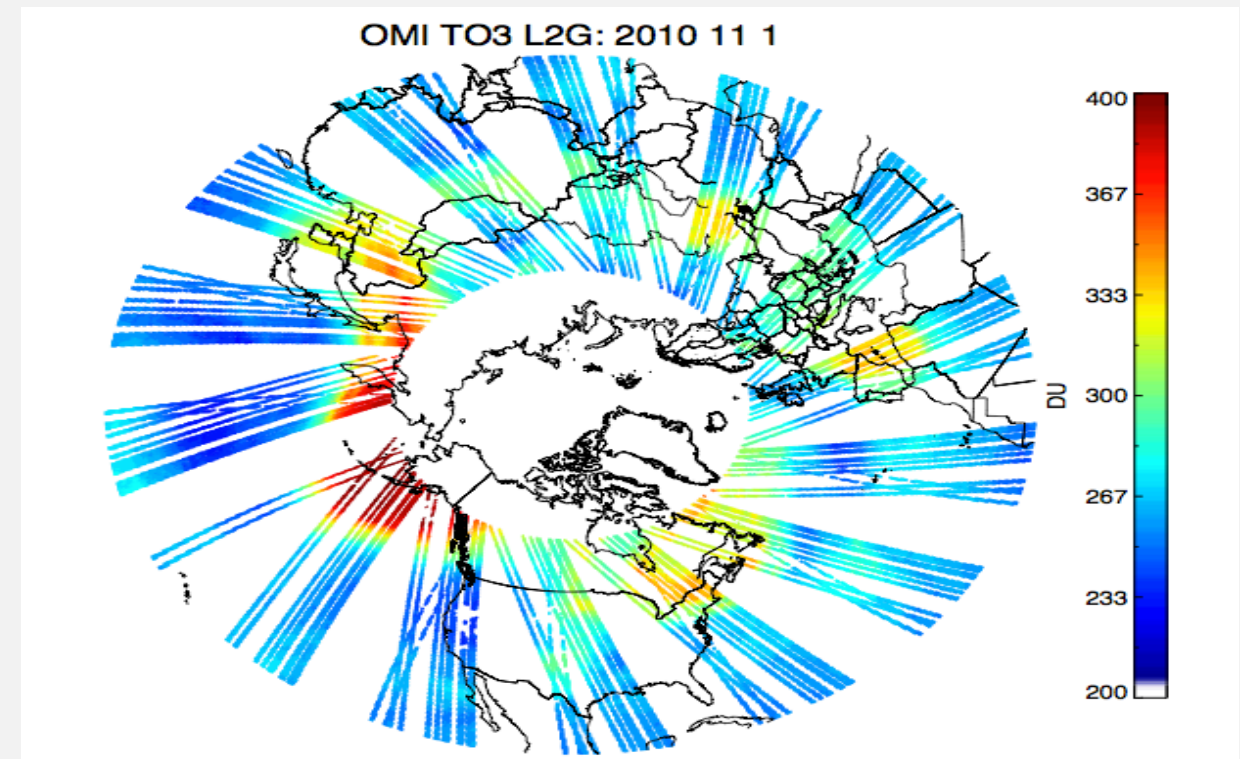
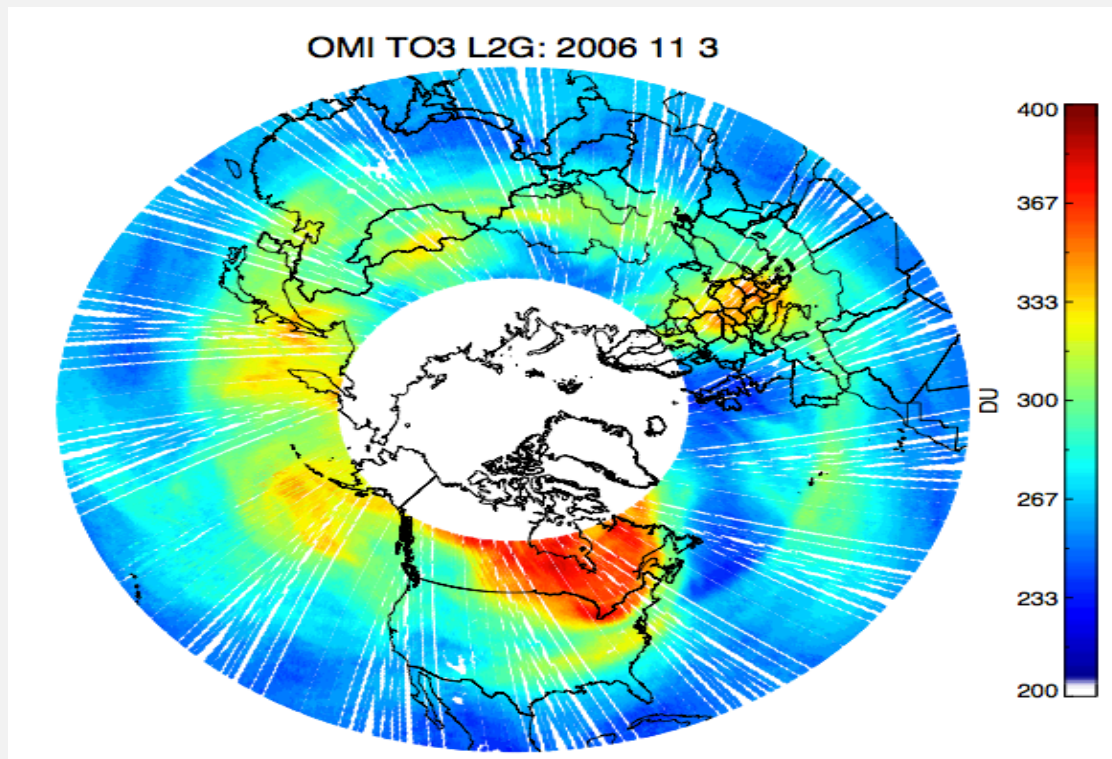
Data Granule


- Product File
 - covers sunlit portion of the orbit with an approx. 2,600 km wide swath
 - contains 60 binned pixels or scenes per viewing line
- 14 or 15 granules are produced daily, providing fully contiguous coverage of the globe



Important Information Regarding OMI

- Almost 50% data loss since 2008 (row anomaly effect)
- Affects O_3 , SO_2 , and to some extent NO_2 OMI products



A satellite image of the Mediterranean region, showing the sea, surrounding landmasses, and cloud patterns. A semi-transparent rectangular box is overlaid on the image, covering the central and eastern parts of the Mediterranean. Inside this box, the text 'O3 and HCHO' is displayed. The background image shows the Iberian Peninsula, North Africa, and parts of Europe and Asia, with various cloud formations and land features visible.

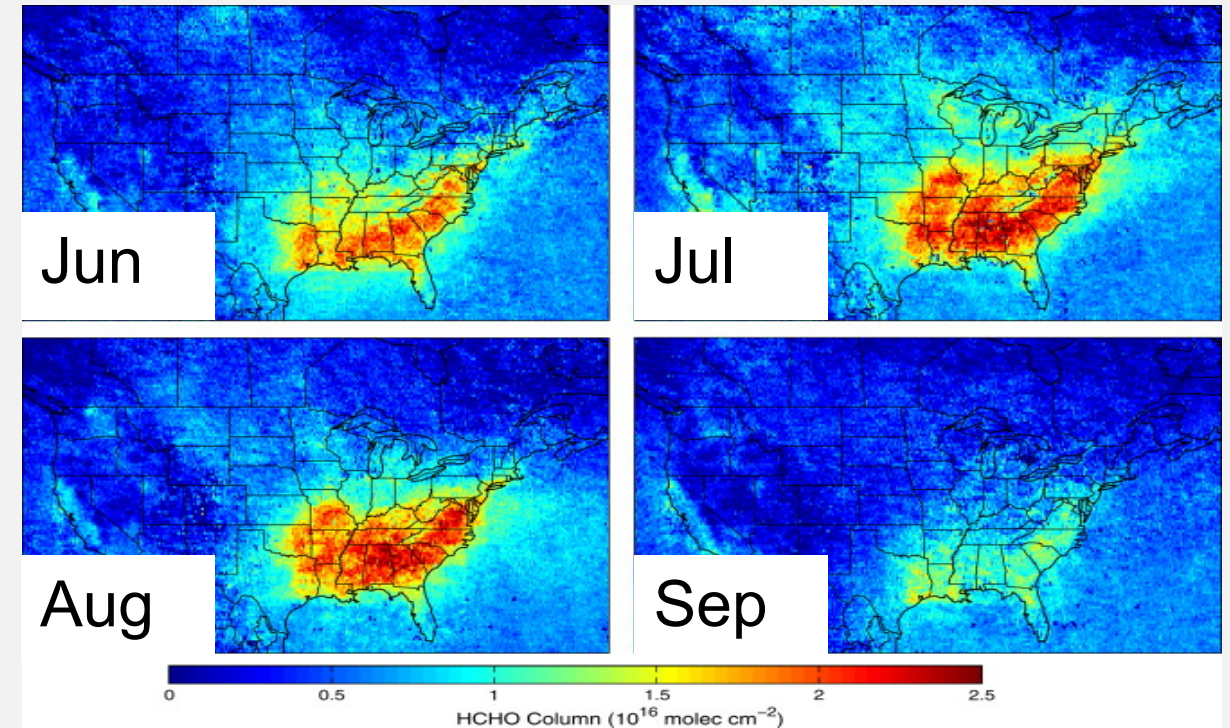
O_3 and HCHO

OMI Ozone in the Troposphere


- Why measure tropospheric ozone?
 - Ozone is a tropospheric pollutant with negative health impacts for humans (e.g. aggravation of asthma and other lung diseases) as well as ecosystems (e.g. crop damage)
 - Ozone also plays an important role in the chemistry of the troposphere
- OMI is **not** sensitive to ozone near the surface
- Tropospheric ozone products cannot be used for air quality monitoring
- Retrieval of boundary layer O₃ from satellite remote sensing remains a daunting task
 - Separation of total column into stratospheric and tropospheric contribution
 - Potential for significant free tropospheric contribution to the tropospheric column

OMI Formaldehyde (CH₂O)

- Why measure formaldehyde?
 - Formaldehyde is an ozone precursor and can serve as a proxy for total VOC chemical reactivity and isoprene emissions
- Daily and monthly gridded data (0.25° x 0.25°) available from <http://h2co.aeronomie.be/>
- Or Level 2 gridded data for the NASA/Smithsonian retrieval can be found:
 - https://disc.gsfc.nasa.gov/datasets/OMHCHO_V003/summary
- Caution should be used when using these data for quantitative analyses
 - When compared to observations, satellite observations of HCHO are biased low



Source: Martin, Randall. Satellite remote sensing of surface air quality. Atmospheric Environment 42(34), 7823-7843, 2008.

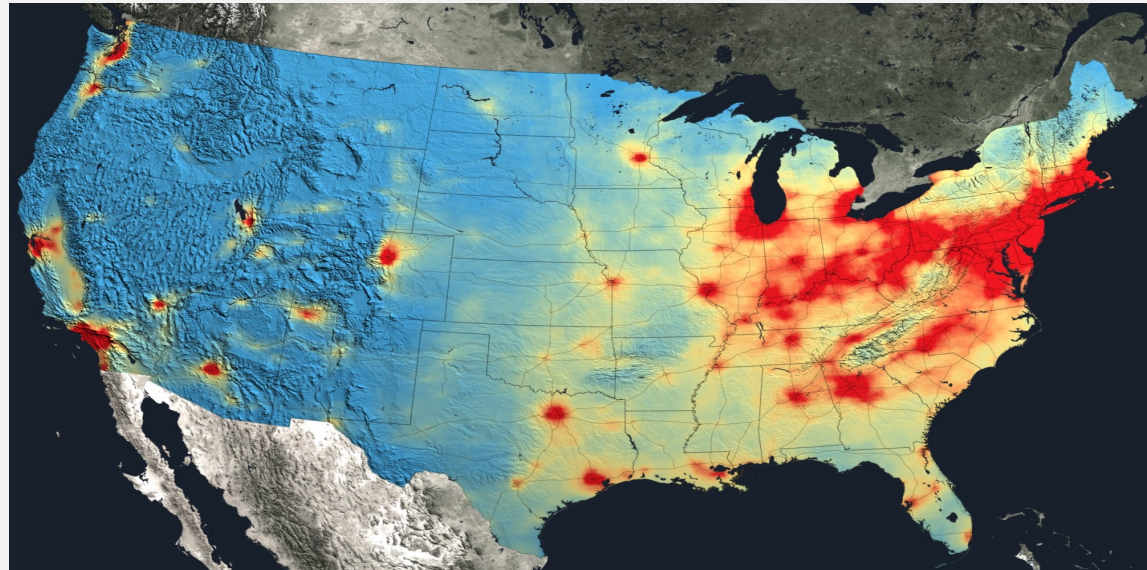


A satellite map of the North Atlantic Ocean and surrounding landmasses, including North America, Europe, and Africa. The map displays tropospheric column NO₂ and volcanic SO₂ concentrations. A large, semi-transparent grey rectangular box covers the central part of the image, containing the text "Tropospheric Column NO₂" and "Volcanic SO₂". The map shows various geographical features, including the Gulf of Mexico, the Atlantic Ocean, and the European continent. Red outlines and dots are visible on the map, likely indicating specific locations of interest or data points. A thin black line is also visible, running horizontally across the map.

Tropospheric Column NO₂
Volcanic SO₂

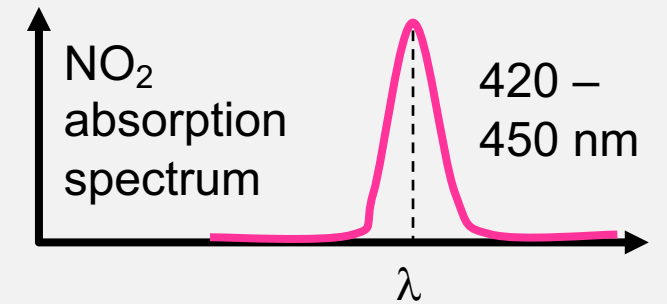
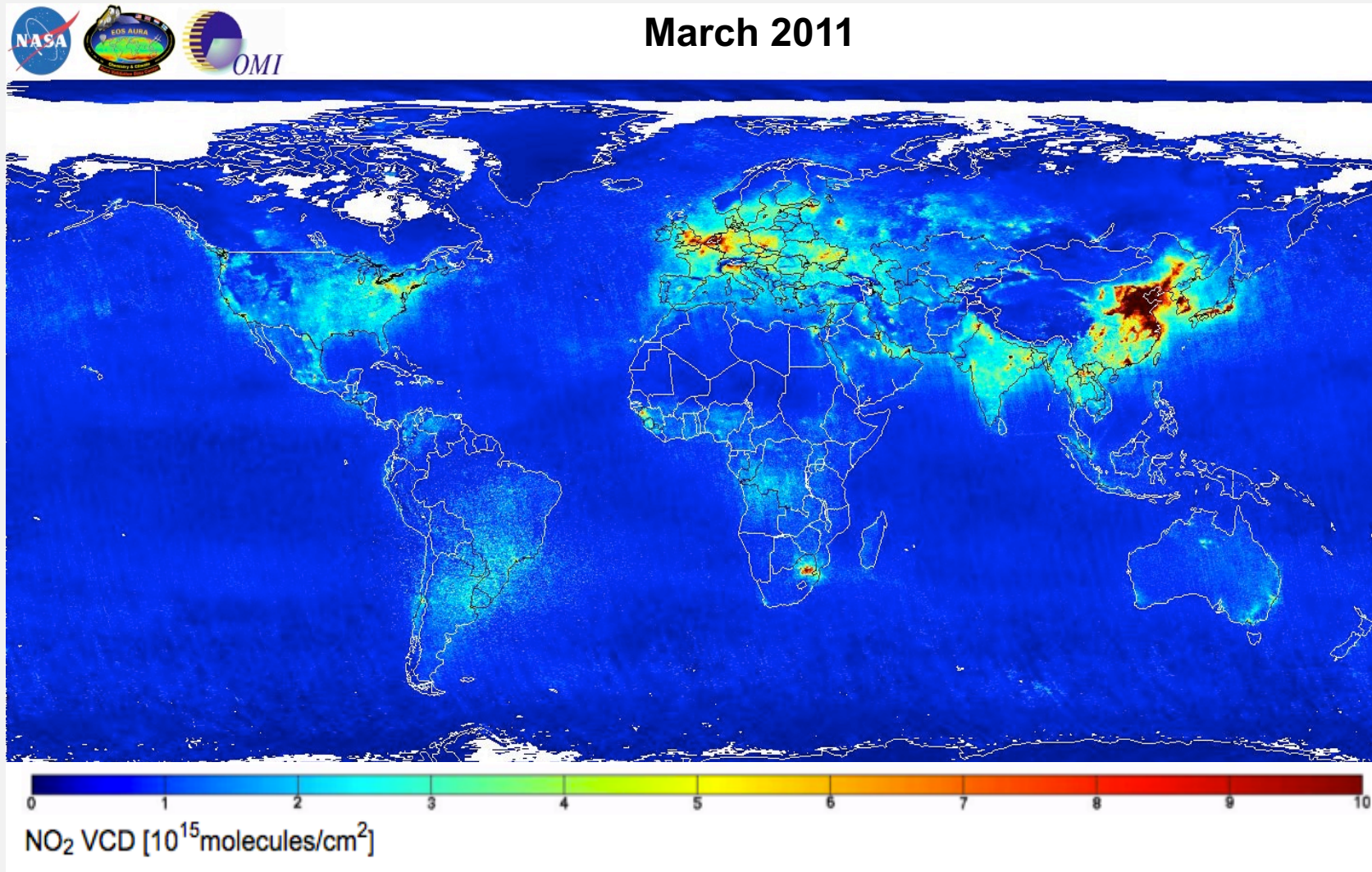
Nitrogen Dioxide (NO₂)

- Why measure NO₂?
 - NO₂ is an ozone precursor and health irritant
 - Sources: Fires, industrial and transportation sources, stationary sources (e.g. power plants), *but* emissions can vary depending on fuel type and conditions
 - High concentrations in the planetary boundary layer (PBL)
 - Satellite observations have been used in inverse modeling studies



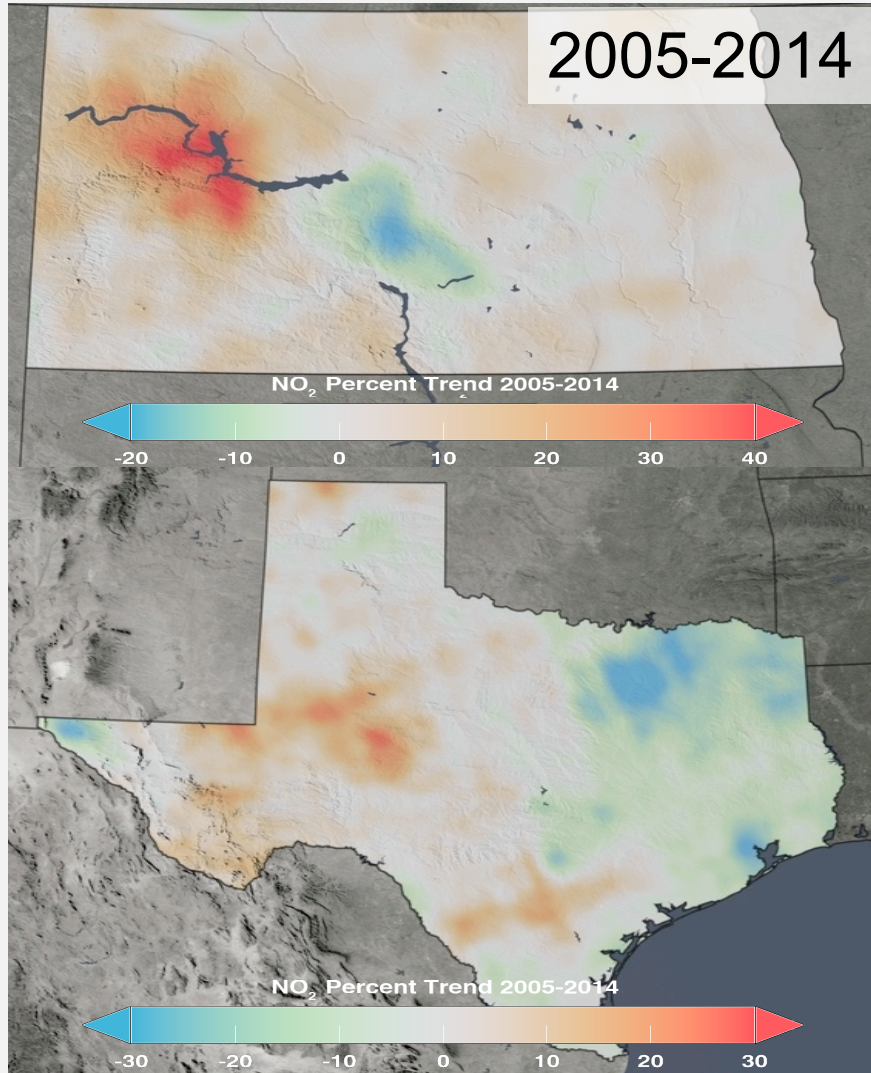
Source: Duncan, B.N. et al. (2016)

Global view of tropospheric column NO₂ from OMI



airquality.gsfc.nasa.gov/

OMI Detects NO₂ Increases from ONG Activities



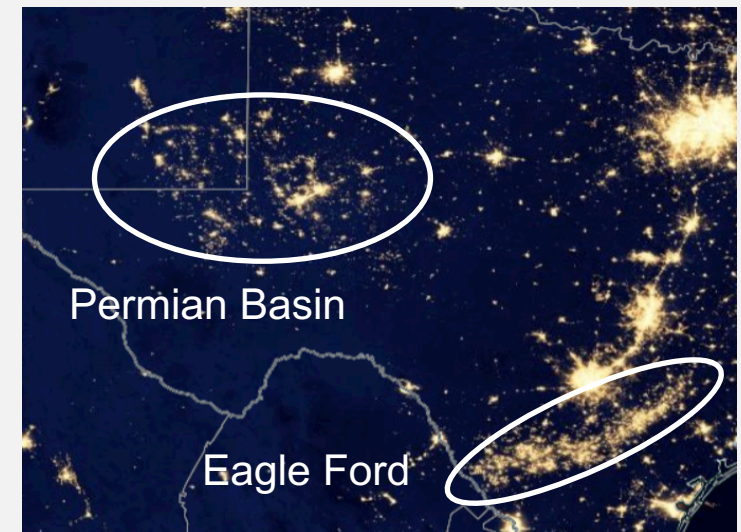
North Dakota

Texas

Courtesy of: Bryan Duncan

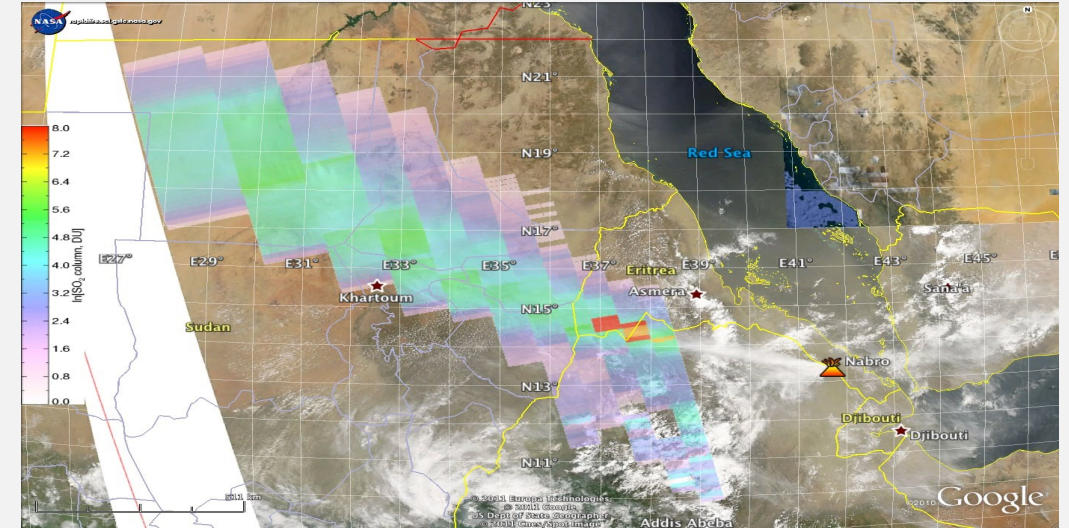


Suomi NPP VIIRS Lights at Night



OMI SO₂ in the Boundary Layer

- Why measure SO₂?
 - SO₂ has also been linked to adverse respiratory effects
 - Contributes to acid deposition
 - Sources: Volcanoes, coal and oil burning
- Dataset Short Name = OMSO2e
 - Product Level: 3
 - Daily, beginning October 1, 2004
 - Resolution: 0.25° x 0.25°
 - File Size (approx): 5 mb

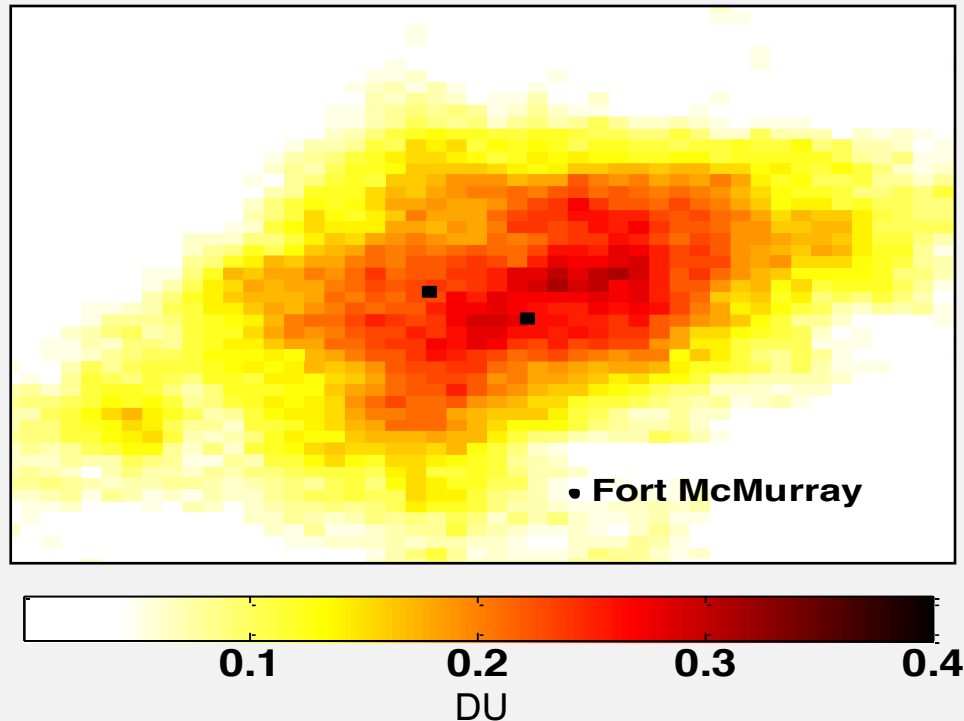


Aqua MODIS visible image of the Nabro (Eritrea) eruption on June 13, 2011 and the SO₂ plume overlaid.

- Screened for data quality (e.g. OMI row anomaly, clouds, etc.)
- https://disc.sci.gsfc.nasa.gov/datasets/OMSO2e_V003/summary

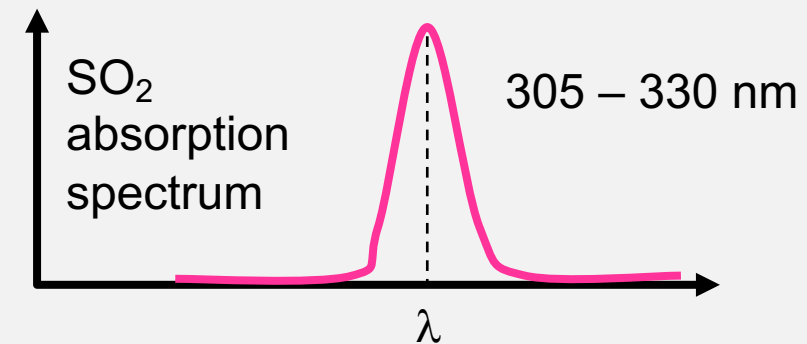
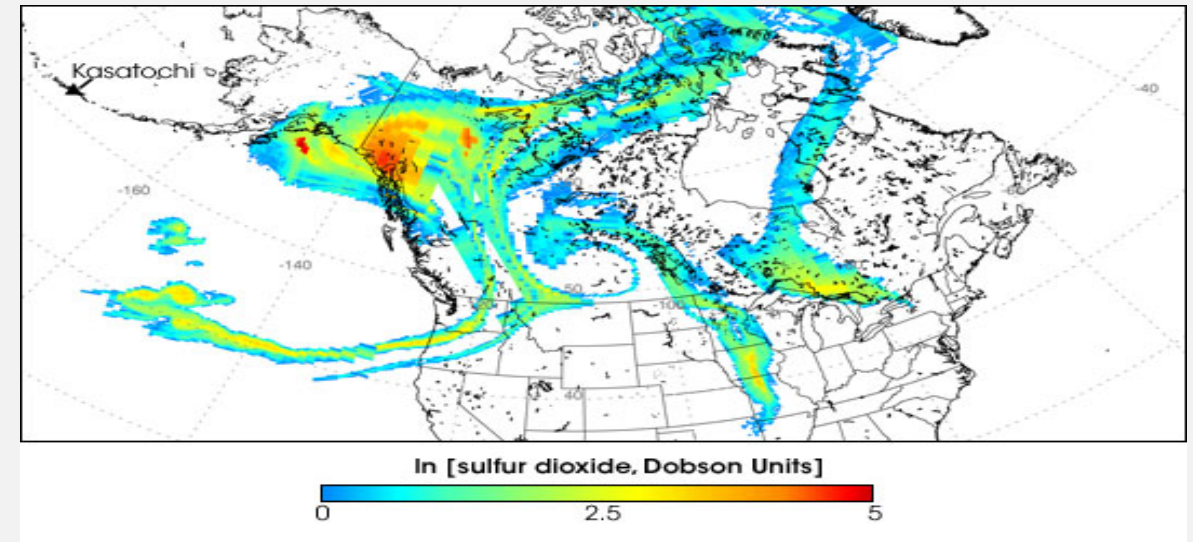
Perspective: What is Considered High SO₂?

2005-2010 Mean SO₂ Over Canadian Oil Sands



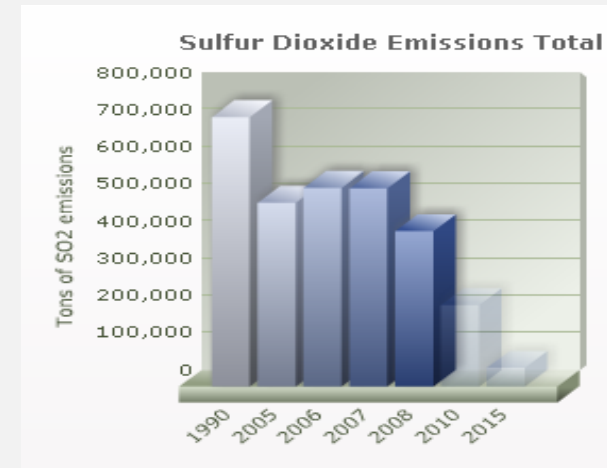
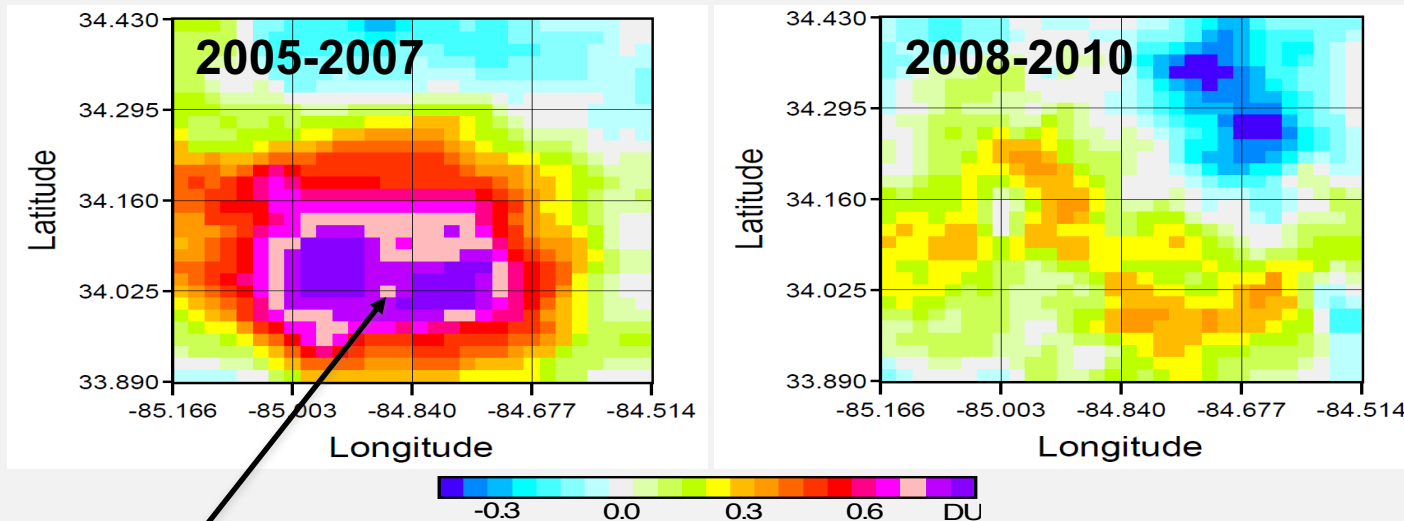
McLinden, C. A., et al. (2012), Air quality over the Canadian oil sands: A first assessment using satellite observations, *Geophys. Res. Lett.*, 39, L04804, doi:10.1029/2011GL050273.

OMI SO₂ from Kasatochi Volcano August 8-12, 2008



Perspective: What is considered high SO₂?

#1 U.S. Source: Bowen Coal Power Plant, Georgia (3500 MW), SO₂ Emissions: 170 kT in 2006



“In **2008**, the mammoth construction program yielded the first scrubbers, sophisticated equipment that will reduce our overall systems emissions by as much as 90 percent”

Georgia Power website

Source: V. Fioletov, et al., 2011

OMI SO₂ Gridded Product Summary

SO ₂ Product	Level	Data Short Name	Altitude Sensitivity	Use
PBL SO ₂	L3 0.25° x 0.25°	OMSO2e	0.6 km	Fossil fuel, industry
TRL SO ₂	L2G 0.125° x 0.125°	OMSO2G	3 km	Optimized for volcanic degassing
TRM SO ₂	L2G 0.125° x 0.125°	OMSO2G	8 km	Plumes from moderate eruptions
STL SO ₂	L2G 0.125° x 0.125°	OMSO2G	18 km	Explosive volcanic eruptions

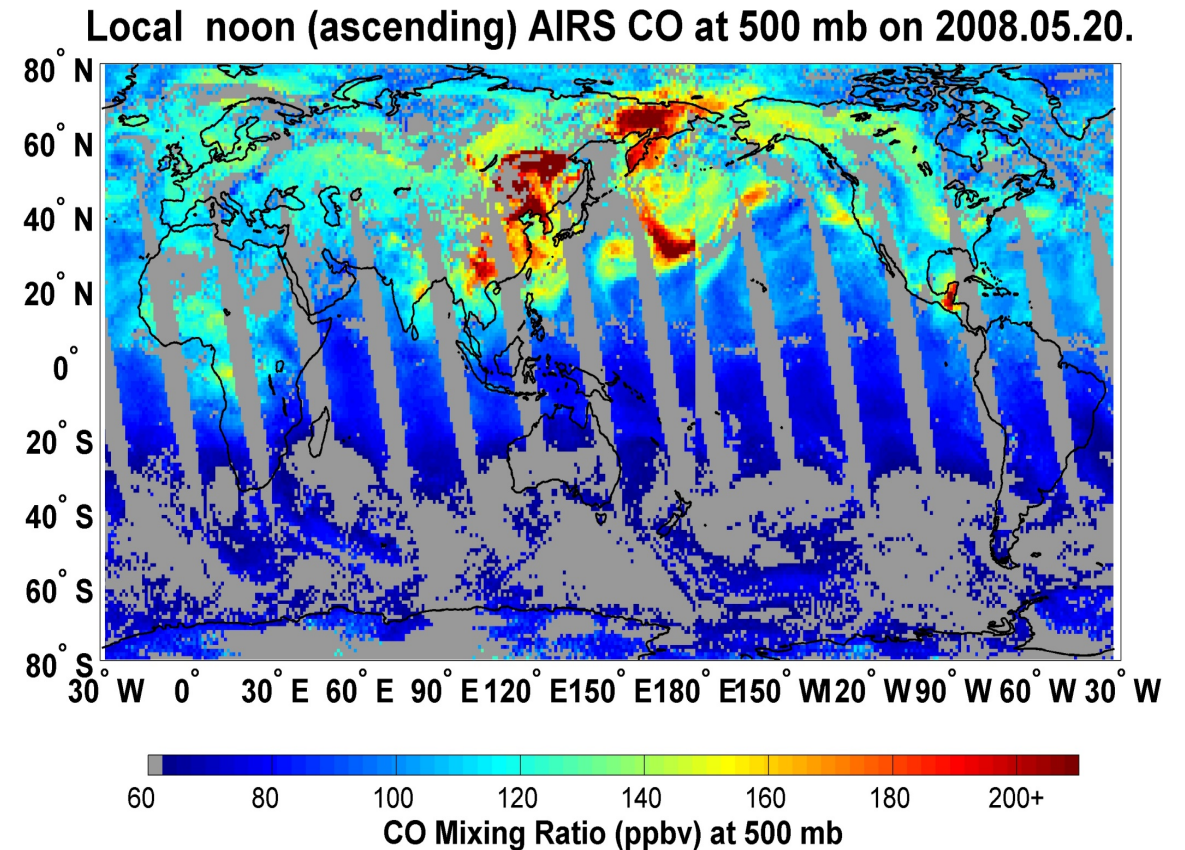
Note: The L2G data is not screened for clouds, solar zenith angle, quality flags, and row anomalies

A satellite image of the North Atlantic Ocean, showing swirling cloud patterns and the surrounding landmasses of North America and Europe. A semi-transparent rectangular box is overlaid on the right side of the image, containing the text 'Carbon Monoxide (CO)'.

Carbon Monoxide (CO)

Carbon Monoxide

- Why measure CO?
 - Major global precursor for O_3 , and dominant sink for OH
 - Relatively long lifetime (~1-2 months) makes it a useful tracer of transport
- Typically measured as a column density
- Instruments (e.g. MOPITT, AIRS) tend to have good sensitivity to CO in the mid-troposphere (~500 mb)
- Current sensors: AIRS, MOPITT, IASI

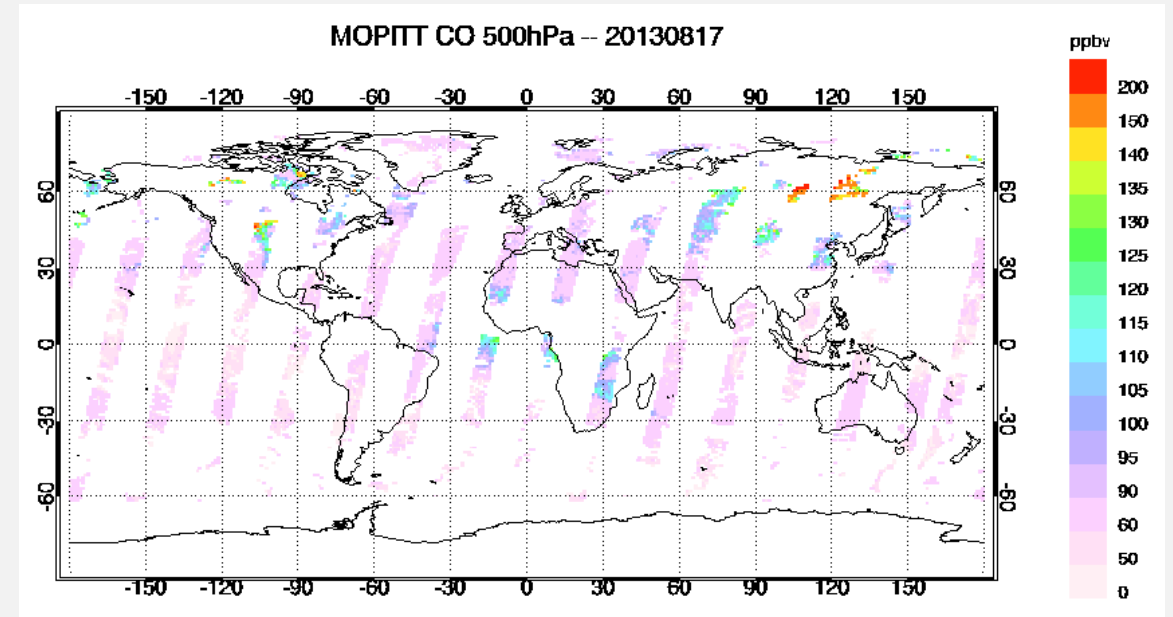


Measurements of Pollution in The Troposphere (MOPITT)

<https://www2.acom.ucar.edu/mopitt>

- Operational since 2000
- Global coverage every 3 days
- Nadir, Pixel size
 - 22 km² at nadir
- Swath Width: 640 km
- Equator Crossing Times
 - 10:30 (descending)
- Three retrievals
 - TIR: Highest temporal stability
 - NIR: daytime, column only
 - TIR/NIR (Joint): Greatest sensitivity to lower troposphere, but larger errors

Image Source: [NCAR UCAR](https://www2.acom.ucar.edu/mopitt)

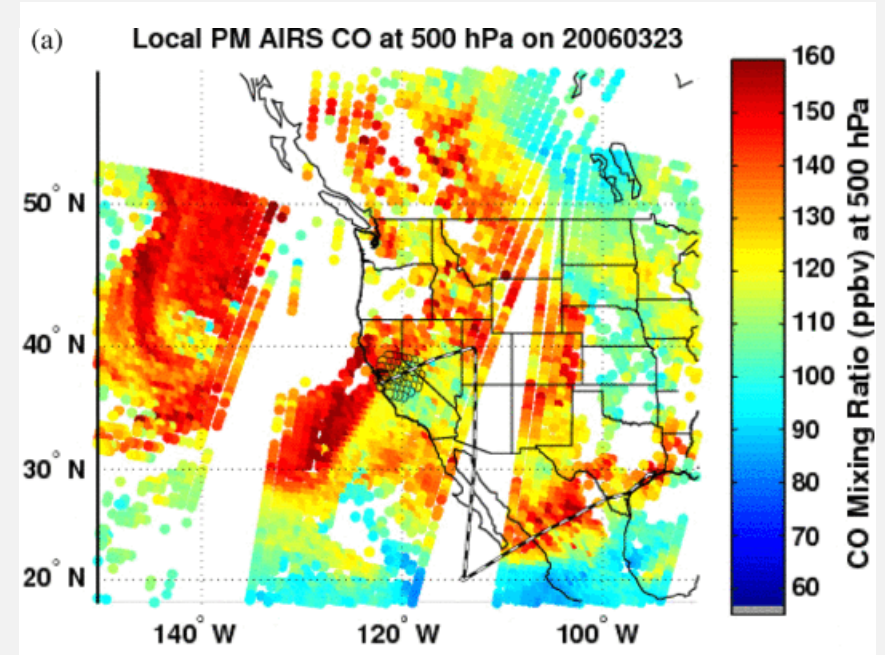


- Profile Measurements:
 - 10 pressure levels including the surface (surface – 100 hPa)
- Data source:
 - Level 2 pixel
 - Level 3 gridded 1° x 1° resolution

Atmospheric Infrared Sounder (AIRS)

<http://airs.jpl.nasa.gov/>

- Operational since Sep 2002
- Daily coverage
- Nadir, Pixel size:
 - 14 km at nadir
 - 41x21 km edges
- Swath Width: 1,650 km
- Equator Crossing Times
 - 13:30 (ascending)
 - 1:30 (descending)

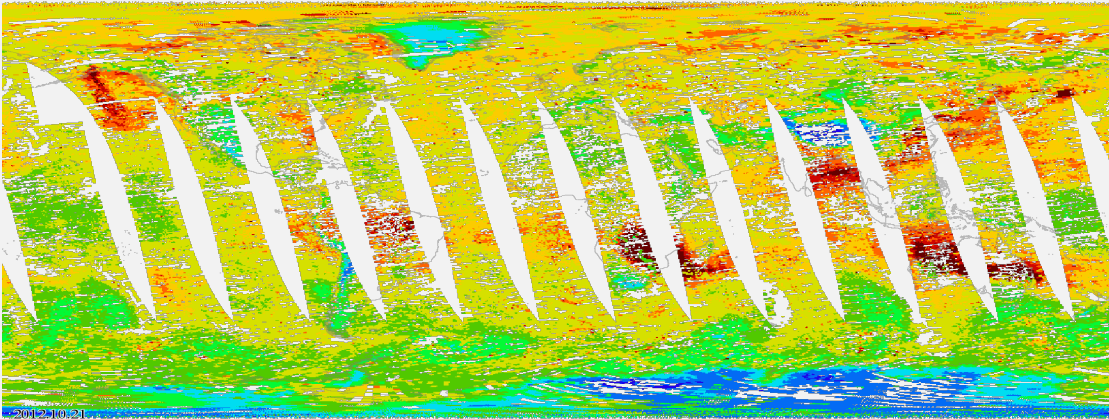


- Profile Measurements:
 - 9 vertical layers
 - 901.866 hPa – 0.16 hPa
- Data:
 - Level 2 pixel
 - Level 3 gridded 1° x 1° resolution

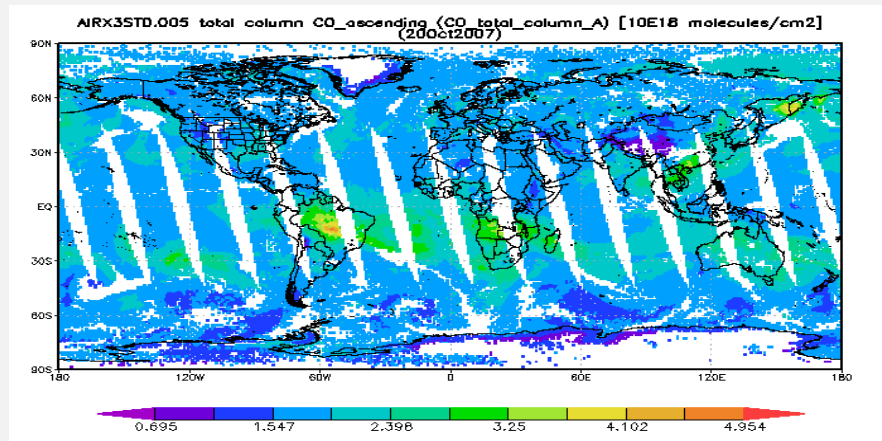
Source: Figure 6a from McMillan et al. (2011)

AIRS vs. MOPPITT CO – Daily Coverage

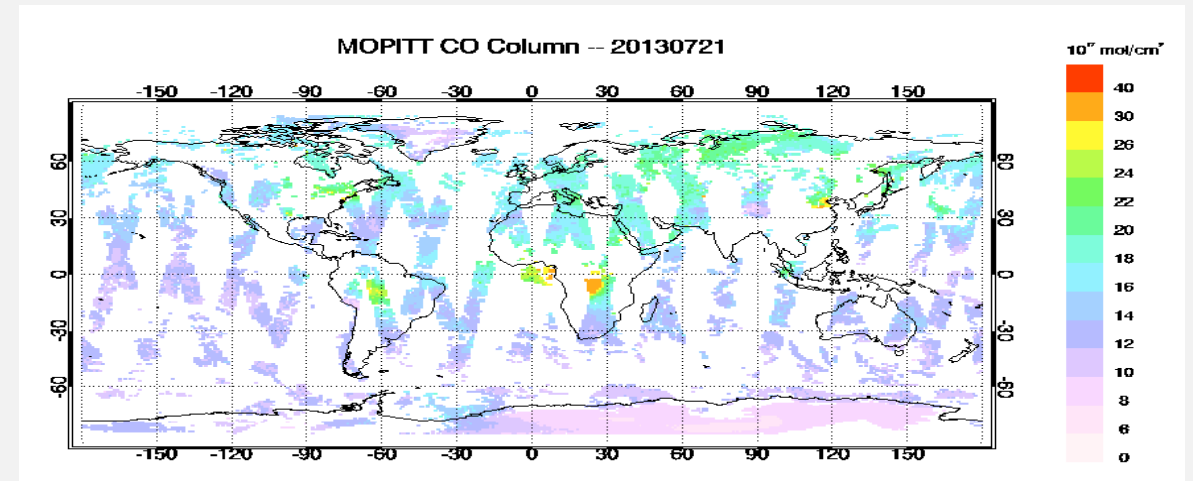
AIRS Level 2 from NRT Website



AIRS Level 3, 1°x1° from Giovanni



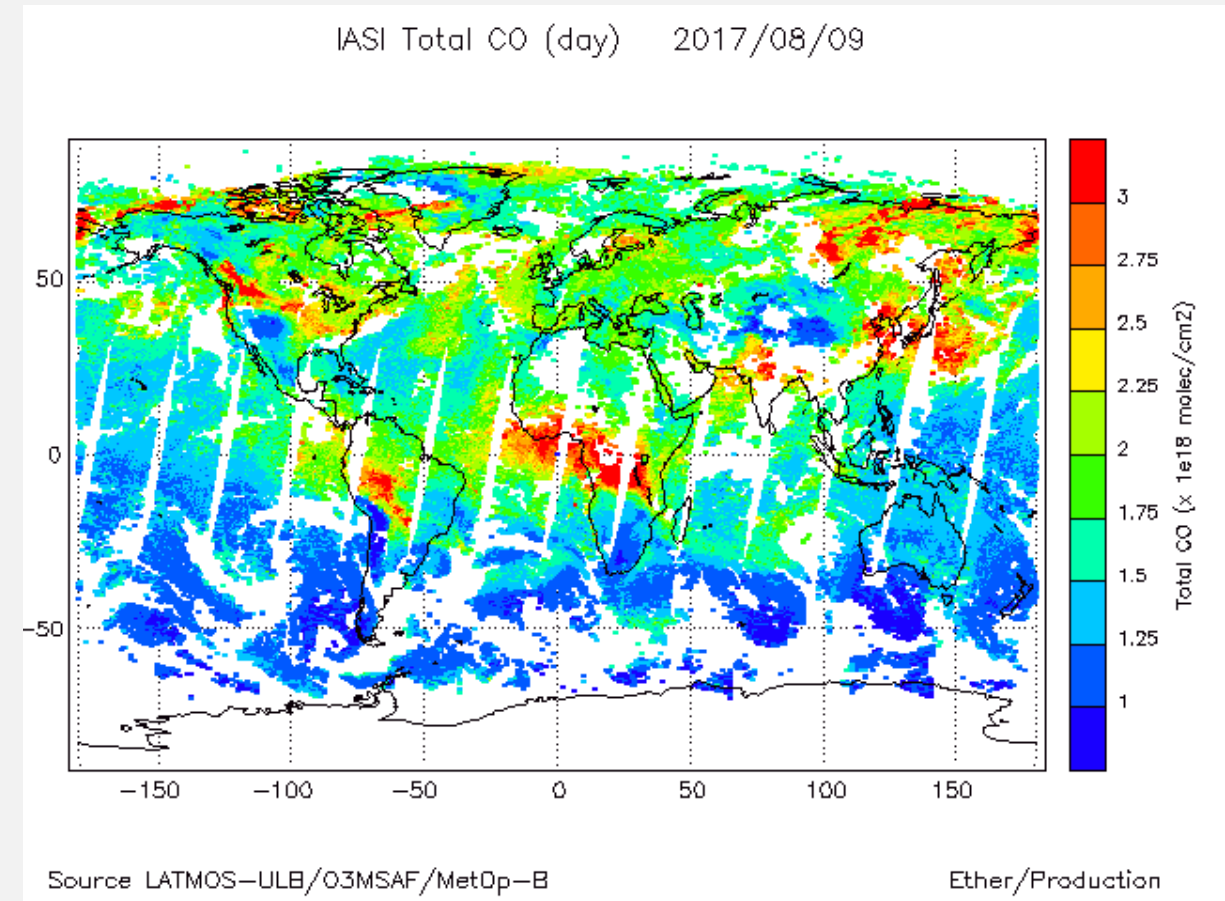
MOPPITT Level 3, 1°x1°



Infrared Atmospheric Sounding Interferometer (IASI)

<http://bit.ly/ESA-IASI>

- Operational since 2006
- Daily coverage
- Nadir, Pixel size
 - 12 km² at nadir
- Swath Width: 2200 km
- Equator Crossing Times
 - 9:30 (descending)
 - 21:30 (ascending)
- CO Columns available in NRT
 - Within three hours of observation
- 18 layers



Comparison Chart - CO

	MOPITT	AIRS	IASI
Product / Pixel size	22 x 22 km	14 x 14 km	12 x 12 km
Swath Width	650 km	1,650 km	2,200 km
Global Coverage	3 days	2x per day	2x per day
Overpass Time	10:30	13:30	9:30, 21:30
Product Resolution	L3: 1° Grid	L3: 1° Grid	NO L3 Product
Products Available	L2 L3, Daily, Monthly	L2 granule L3	L2 NOAA & ESA
Vertical Sensitivity	mid & lower troposphere	mid troposphere	mid tropo-sphere
Product Accuracy	TIR: 10% Near Surface: 30%	10-20%	<10%

Questions and Discussion

- Name a difference between retrievals of trace gases and retrievals of aerosols.
- What is the difference between Dobson unit and ppmv?

A satellite image of the North Atlantic Ocean and surrounding landmasses, including North America, Europe, and Africa. A semi-transparent grey rectangle is overlaid on the ocean. Within this rectangle, several landmasses are outlined in red, including Greenland, Iceland, and parts of the British Isles and Scandinavia. A thin black horizontal line is drawn across the rectangle, passing through the red-outlined areas.

Questions
